

Negative S and Light New Physics*

P. Bamert^a and C.P. Burgess^{a,b}

^a *Institut de Physique, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland.*

^b *Physics Department, McGill University*

3600 University St., Montréal, Québec, CANADA, H3A 2T8.

Abstract

The several sigma difference between SLD's recent precise measurement of A_{LR} and the corresponding LEP results tends to reinforce the earlier trends in the data towards negative values for the Peskin-Takeuchi parameter S and T . Motivated by this not yet statistically significant, but suggestive, trend, we explore which kinds of new particles can (1) contribute dominantly to new physics through oblique corrections, (2) produce negative values for S and T , and (3) not be in conflict with any other experiments, on or off the Z resonance. We are typically led to models which involve new particles with masses that are not much heavier than $M_Z/2$, and so which would also have implications for other experiments in the near future. We show how the analysis of such 'light-new-physics' models in terms of oblique parameters requires the interpretation of the data in terms of modified parameters, S' and T' , whose difference from S and T improves the available parameter space of the models.

* Research supported by the Swiss National Foundation.

1. Introduction

As the accuracy of the measurements of the properties of the the Z -boson resonance continue to improve, the tests of the standard electroweak theory are reaching new levels of precision [1]. Recently the numerous measurements at CERN's Large Electron Positron ring have been joined by the measurement of the left-right asymmetry, A_{LR} , at the Stanford Linear Collider [2]. This last measurement — touted as the most accurate single electroweak measurement on the Z resonance — implies an electron- Z coupling which lies some $2.5\text{-}\sigma$ away from the corresponding combined LEP values for the same number. The difference between this coupling as measured by A_{LR} , and by the τ -polarization asymmetry, $A_e(P_\tau)$, at LEP is over 3σ [1], [3]. When analyzed in terms of new-physics contributions to the vector boson vacuum polarizations [4] — *i.e.* in terms of the oblique parameters, S, T and U [5] — the A_{LR} result tends to push S to more negative values. (A recent fit [6], for instance, gives $S = -0.58 \pm 0.30$ and $T = -0.38 \pm 0.34$, for $m_t = 165$ GeV and $m_H = 300$ GeV. For $m_t = 174$ GeV, on the other hand, S does not change appreciably but the central value for T decreases by $\simeq 0.2$.) Although this does not yet represent a statistically significant deviation from the Standard Model (SM), it remains tantalizing that the earlier trend toward more negative central values for S is reinforced by the newer results.

With such spiffy new experimental numbers a theorist's fancy inevitably turns to thoughts of interpretation. A negative value for S is particularly interesting in this regard, since this was found to be reasonably difficult to obtain within the context of technicolour models [7]. (A recent discussion in terms of new gauge bosons, motivated by the SLD A_{LR} measurement, can be found in Ref. [8].)

In this note we construct several types of models which contribute to precision electroweak measurements dominantly (or, for some models, exclusively) through oblique corrections. Furthermore, they do so *as if* S were negative. The qualification ‘as if’ is required because the quantities which appear in the expressions for the observables are, in general, not S, T and U as they are usually defined. The basic point is that if the oblique new physics should not be heavy in comparison to the W and Z masses, then its contribution

to all of the low-energy neutral-current data generally requires two parameters — V and X of Ref. [9] — in addition to the usual three. (The third new quantity, W , of Ref. [9] contributes only to the W -boson width and is ignored here.)

The necessity for additional parameters might come, at first thought, as a surprise since oblique contributions to Z -pole physics and M_W only involve three independent observables. One might therefore expect to be able to choose these to be the standard quantities, S, T and U , provided one chose to work exclusively with M_W and measurements on the Z resonance. This turns out not to be true.¹ (The same objection does not apply to the ϵ formalism of Ref. [10], but *only* if M_W and Z -pole data are all that are considered.) It *is*, of course, true that, for Z -pole physics and M_W only, all oblique corrections to observables can be summarized into three independent quantities. It is convenient to choose these to be:

$$S' = S + 4s_w^2 c_w^2 V + 4(c_w^2 - s_w^2) X, \quad (1)$$

$$T' = T + V, \quad (2)$$

$$U' = U - 4s_w^2 c_w^2 V + 8s_w^2 X, \quad (3)$$

where s_w and c_w denote the sin and cosine of the weak mixing angle, θ_w .

With this choice S', T' and U' have two very convenient properties. First, they reduce to S, T and U in the limit of heavy new physics, since in this case V and X both become completely negligible. Second, these definitions ensure that all Z -pole observables (and M_W) depend on S', T' (and U') in precisely the same manner as they do on S, T and U in the usual analyses. As a consequence, the results of any fits to the present LEP and SLD data, together with the W mass, apply verbatim to S', T' and U' . The ‘trend’ of the data can therefore be more properly phrased as a trend towards negative values for S' (and T'), with the fit of Ref. [6] quantitatively implying $S' = -0.58 \pm 0.30$ and $T' = -0.38 \pm 0.34$ for the given values of m_t and m_H . S and T are themselves only constrained independently of this by the additional data at $q^2 \simeq 0$.

¹ We thank David London, Ivan Maksymyk and Probir Roy for useful conversations on this point.

This difference between the definitions of the primed and unprimed parameters is not merely an academic point. We find in our search for models that it frequently happens that S' and T' take their most negative values when the new physics is light enough to permit positive, or slightly negative, values for S and T to be compensated in S' and T' by negative contributions to V and X . Since the models to which we are led therefore typically involve comparatively light particles, they can be expected to have more direct experimental implications in experiments in the comparatively near future.

2. Models

We now turn to the construction of models. Our purpose is to survey the parameter space of simple models to find those for which S' and T' are both negative, and are both roughly the same size. We take a conservative approach and simply supplement the SM by a few additional spin-zero or spin-half particle types, and explore the one-loop oblique parameters they generate as a function of the assumed quantum numbers and masses of the new particles. Of particular interest among our results are some particular cases of new particles, since these arise quite naturally among the low-energy spectrum of more complicated, but theoretically better motivated, models (such as the supersymmetric standard model *etc.*).

2.1) Scalars

Our first class of models simply consists of complicating the SM Higgs sector by adding various scalar multiplets to the standard $Y = \frac{1}{2}$ doublet. Since, at one loop, each new multiplet contributes additively to the oblique parameters, we may consider the contributions of such new particles one multiplet at a time.

The contributions of scalar multiplets to the parameters $S - X$ have been computed in Refs. [11] and [12].² We have surveyed the parameter space of couplings and masses for

² In fact, it is amusing that one of the cases worked out in Ref. [11] furnishes an example of a scalar multiplet for which S' and T' take the central values of the fit of Ref. [6]. The model which does so is

| Multiplet ($3 \times 2 \times 1$) | Optimal Masses (GeV) | S' | T' | U' | S | T | U |
|---|---|-------|--------|-------|--------|---------|-------|
| $(\mathbf{1}, \mathbf{1}, Y = 1)$ | $m = 50$ | -0.01 | -0.006 | 0.002 | -0.003 | 0 | 0.003 |
| $(\mathbf{1}, \mathbf{2}, Y = \frac{1}{2})$ | $\begin{pmatrix} m_1 \\ m_0 \end{pmatrix} = \begin{pmatrix} 62 \\ 50 \end{pmatrix}$ | -0.04 | -0.03 | 0.03 | -0.03 | 0.003 | 0.003 |
| $(\mathbf{1}, \mathbf{2}, Y = 0)$ | $\begin{pmatrix} m_{+\frac{1}{2}} \\ m_{-\frac{1}{2}} \end{pmatrix} = \begin{pmatrix} 50 \\ 72.5 \end{pmatrix}$ | -0.02 | -0.01 | 0.02 | -0.01 | 0.009 | 0.003 |
| $(\mathbf{1}, \mathbf{2}, Y = \frac{3}{2})$ | $\begin{pmatrix} m_2 \\ m_1 \end{pmatrix} = \begin{pmatrix} 51 \\ 50 \end{pmatrix}$ | -0.09 | -0.06 | 0.04 | -0.03 | 0.00002 | 0.01 |
| $(\mathbf{1}, \mathbf{3}, Y = 0)^\dagger$ | $\begin{pmatrix} m_1 \\ m_0 \\ m_{-1} \end{pmatrix} = \begin{pmatrix} 50 \\ 78 \\ 50 \end{pmatrix}$ | -0.06 | -0.04 | 0.1 | -0.03 | 0.03 | 0.07 |
| $(\mathbf{1}, \mathbf{3}, Y = 1)$ | $\begin{pmatrix} m_2 \\ m_1 \\ m_0 \end{pmatrix} = \begin{pmatrix} 63 \\ 57 \\ 50 \end{pmatrix}$ | -0.2 | -0.1 | 0.1 | -0.1 | 0.003 | 0.01 |

[†] Self-conjugate multiplet.

Table I: Exotic Scalars

One-loop oblique electroweak parameters due to exotic scalar multiplets. This table displays the masses which ‘optimize’ the oblique electroweak parameters in the sense described in the text, together with the resulting optimal values. $(\mathbf{r}_1, \mathbf{r}_2, Y=y)$ denotes the representation of $SU_c(3) \times SU_L(2) \times U_Y(1)$ in which the scalars transform, and m_q represents the mass of a state having electric charge q .

various scalar multiplets, searching for the regions which can contribute negatively to S' and T' . We present the results of this survey in two different ways. First, Figs. (1) through (4) illustrate the dependence of the oblique parameters on scalar masses, by displaying the

the eleven-dimensional multiplet having weak isospin $J=5$ and weak hypercharge $Y=-\frac{1}{2}$, and for which the eleven states are equally split in squared mass, starting with the lowest-mass state at $m_1=134$ GeV and the highest-mass state at $m_2=159$ GeV. With these choices one finds $S'=-0.58$ and $T'=-0.38$.

region of the $S' - T'$ plane which can be reached by varying the scalar masses from 50 to 200 GeV. Next, we display in Table I the values for these masses which are ‘optimal’, meaning that they maximize the magnitude of the contribution to S' and T' subject to the condition that their ratio satisfies $S'/T' = (0.58/0.38)$. We choose this ratio as indicating the direction in the $S' - T'$ plane of the central value of the fit of Ref. [6]. By doing so, we do not intend to argue that this ratio has been definitively determined by the data, but rather to give a quantitative indication of the size that is possible for the oblique parameters in each case. In searching for the masses which are optimal in this sense, we never permit any of our scalar masses to fall below 50 GeV, to avoid the bounds from direct production at LEP [13]. Unless stated otherwise, all of the numbers assume the new multiplets are colour singlets.

We consider the following types of scalar multiplets:

- *Isosinglet Scalars:* The simplest possible scalar multiplet to add is an $SU_L(2)$ singlet. Such particles arise in several interesting theoretical scenarios. They arise: (i) as scalar partners to the right-handed leptons and quarks in supersymmetric models; (ii) in the class of models proposed by Zee [14] some years ago; and (iii) in leptoquark models where they can couple leptons to quarks in unorthodox, but baryon- and lepton-number preserving, ways.

- *Isodoublet Scalars:* $SU_L(2)$ doublets form a particularly well-explored wrinkle to the fabric of the minimal standard model, since a second $Y = \frac{1}{2}$ scalar doublet appears naturally in many of its alternatives. Among the models which naturally incorporate doublet scalars are: (i) supersymmetric models, for which the extra scalars arise as an additional Higgs doublet (with $Y = \frac{1}{2}$), as well as the scalar superpartners of the left-handed quarks and leptons (having $Y = \frac{1}{6}$ and $\frac{1}{2}$ respectively); and (ii) models of (spontaneous or explicit) CP -violation at the electroweak scale, such as might be required for electroweak baryogenesis. Since the superpartners of the left-handed quarks are subject to stringent CDF bounds [15] they cannot contribute significantly to negative (S', T') , as can be seen from Fig. (2). For this reason they are omitted from Table I.

- *Isotriplet Scalars:* Isotriplet scalars arise in many situations, such as in left-right symmetric models. Typically, if these fields are permitted to acquire vacuum expectation values (*vev*'s), they can spell trouble for low-energy weak-interaction measurements, through their tree level contributions to the rho parameter (*i.e.* T). We sidestep these bounds by assuming all *vev*'s to be zero.

Several features emerge from an inspection of Table I and Figs. (1) through (4).

- *1:* All of the allowed regions in these figures include the origin, $S' = T' = 0$, with the corollary that it is always possible to produce negative values for S' and T' . There is a simple explanation why this is always so for scalars, even though, as we shall see, the same is *not* true for fermions. The main point is that all of the oblique electroweak parameters must vanish in the limit that the new physics becomes heavy in an $SU_L(2) \times U_Y(1)$ -invariant way. And, unlike for fermions, gauge-invariant masses are *always* possible for scalar multiplets.
- *2:* We generally find the largest values for S' and T' arising from the smallest values for the scalar masses. As a result, the most important regions of parameter space are precisely those for which the difference between S and S' and T and T' is the most important.
- *3:* Although S' frequently becomes more negative for large splittings within a scalar multiplet, the growth of T in this limit invariably drives T' positive, thereby forcing a preference for roughly equal masses within the multiplet.
- *4:* Typically, larger values for S' and T' are possible given larger values for Y , or given a larger $SU_L(2)$ representation. This can be most clearly seen from Table I, for which S' increases both with increasing weak isospin, and with increasing Y for fixed weak isospin. The variation with Y is simplest to see for $SU_L(2)$ singlets, for which all of the oblique parameters are simply proportional to Y^2 .
- *5:* The oblique parameters are similarly enhanced if the scalar multiplets couple to the strong gauge group, $SU_c(3)$. In this case all oblique parameters must be multiplied by the dimension, d_c , of the appropriate $SU_c(3)$ representation. (These factors, together with the

factors of hypercharge mentioned earlier, can be quite large. For instance, a colour-sextet $SU_L(2)$ -singlet scalar having $Y = \frac{4}{3}$, as would be required for a Yukawa coupling to two right-handed up-type quarks, has $d_c Y^2 = \frac{96}{9} = 10\frac{2}{3}$.)

Using colour to amplify the oblique corrections does not come without its price, however, since the masses of coloured particles are often subject to more stringent bounds than are those for colour singlets, due to their non-observation in $p - \bar{p}$ [16] and $e - p$ [17] collisions. These bounds can be sensitive to the nature of the new particle's dominant decay mode, however, and so can be more model dependent than are those furnished by LEP.

- 6: The one-loop contributions to oblique parameters are fairly robust, depending solely on the assumed electroweak transformation properties of the multiplet (in the absence of significant mixing amongst various electroweak multiplets). The same is generally not true for the other bounds on new scalar multiplets, since these can depend on such things as the existence and strength of their Yukawa couplings to fermions, as well as on whether or not they acquire nonzero vev 's. In fact, it is quite simple to arrange for such particles to contribute to experiment predominantly through their oblique corrections, just by forbidding (or suppressing) their non-gauge couplings by a (possibly approximate) symmetry.

- 7: Finally, it is clear that provided no particle masses are permitted to fall below 50 GeV, no single scalar particle can by itself account for a large negative value for S' and T' . Should spinless particles be required to explain a trend to negative S' and T' , if this were to persist as the data improves, it would require a number of new scalars, all contributing together to produce the desired-size effect. As we see next, the same need not be true for exotic fermions, whose contributions to oblique parameters can be considerably larger.

2.2) Fermions

We now turn to the addition of exotic fermions of various types to the Standard Model. As we found for scalars, at one loop we may consider separately the contribution

| Multiplet ($3 \times 2 \times 1$) | Optimal Masses (GeV) | S' | T' | U' | S | T | U |
|---|--|-------|-------|------|-------|------|-------|
| $(\mathbf{1}, \mathbf{2}, Y = -\frac{1}{2})^*$ | $\begin{pmatrix} m_{\nu'} \\ m_{\ell'} \end{pmatrix} = \begin{pmatrix} 50 \\ 92 \end{pmatrix}$ | -0.2 | -0.1 | 0.1 | -0.06 | 0.03 | 0.04 |
| $(\mathbf{3}, \mathbf{2}, Y = \frac{1}{6})^*$ | $\begin{pmatrix} m_{t'} \\ m_{b'} \end{pmatrix} = \begin{pmatrix} 104 \\ 50 \end{pmatrix}$ | -0.1 | -0.08 | 0.3 | -0.01 | 0.2 | 0.1 |
| (extra SM family) | $\begin{pmatrix} m_{\nu'} \\ m_{\ell'} \\ m_{t'} \\ m_{b'} \end{pmatrix} = \begin{pmatrix} 50 \\ 100 \\ 130 \\ 95 \end{pmatrix}$ | -0.06 | -0.04 | 0.2 | 0.04 | 0.1 | 0.05 |
| $(\mathbf{1}, \mathbf{1}, Y = 1)^\dagger$ | $m = 50$ | -0.2 | -0.09 | 0.03 | -0.03 | 0 | 0.03 |
| $(\mathbf{1}, \mathbf{2}, Y = 0)^\dagger$ | $m = 50$ | -0.4 | -0.5 | 0.4 | -0.2 | 0 | 0.009 |
| $(\mathbf{1}, \mathbf{2}, Y = \frac{1}{2})^\dagger$ | $m = 50$ | -0.5 | -0.5 | 0.4 | -0.2 | 0 | 0.005 |

[†] Plus a mirror multiplet with conjugate quantum numbers.

^{*} Plus right-handed isosinglets with identical electric charges.

Table II: Exotic Fermions

One-loop oblique electroweak parameters due to exotic fermions. This table displays the masses which ‘optimize’ the oblique electroweak parameters in the sense described in the text, together with the resulting optimal values. $(\mathbf{r}_1, \mathbf{r}_2, Y=y)$ denotes the transformation properties of the left-handed fermions.

to the oblique parameters of each additional multiplet. A calculation of the six oblique parameters as functions of general fermion masses and couplings is given in Ref. [9].

We present our survey of the parameter space of couplings and masses for the various fermion multiplets in the same way as we did for the exotic scalars: Figs. (5) and (6) plot the dependence of the oblique parameters on the fermion masses, which we take to range from 50 to 200 GeV. Table II displays the values for these masses which are ‘optimal’ in the same sense as was used for the scalars. While optimizing we forbid masses which are smaller than 50 GeV, due to the bounds from direct production at LEP [13]. An exception

is the case of an extra family, where Tevatron bounds [18] on 4^{th} generation quarks are much stronger than are those from LEP. It is possible, should the 4^{th} generation quarks not mix with the usual ones, that the Tevatron bounds would be somewhat weaker. For completeness we therefore include the optimized values for an extra quark doublet, subject only to the LEP bounds, in Table II. All exotic fermions are taken to be colour singlets, except for fourth-generation quarks which are taken to be triplets.

The following types of fermion multiplets are of particular interest:

- *Isosinglet Fermions:* Once more the simplest possible addition is an $SU_L(2)$ singlet. We assume here a mirror fermion for which the left- and right-handed hypercharge are equal, so that arbitrary masses are possible without breaking $SU_L(2) \times U_Y(1)$ invariance.
- *Isodoublet Fermions:* There are two kinds of isodoublet fermions which have been widely considered in the literature. These are (i) sequential quarks and leptons, as would be found in a fourth generation of SM particles, for example, or (ii) $SU_L(2)$ doublets of mirror fermions for which the left- and right-handed parts are both doublets with identical hypercharge quantum numbers.

Several points concerning Figs. (5) and (6) and Table II deserve emphasis.

- *1:* Unlike for the scalar case, it is not necessarily true that the origin, $S' = T' = 0$, need lie in the parameter space of an exotic fermion multiplet, provided that this multiplet lies in a chiral representation of $SU_L(2) \times U_Y(1)$ (as does an additional sequential lepton or quark). A quark multiplet, in particular, definitely favours positive S' , making a real trend to negative S' strongly disfavor such particles. (This is essentially the observation which was originally used to disfavor technicolour models [19].) As may be seen from Fig. (5) or Table II, for a complete additional generation the contribution of extra quarks can be compensated by the additional leptons, but *only* if the additional leptons are reasonably light.
- *2:* As is the case for scalars, the largest values for S' and T' arise from the smallest values for the fermion masses; again emphasizing the difference between the primed and

unprimed oblique parameters.

- 3: We reproduce here the growth of T , and hence the low-energy rho parameter, in the limit that the mass splitting in a standard multiplet becomes large.
- 4: Fig. (6) and Table II display the values for S' and T' that are obtained for a doublet of mirror fermions having various hypercharges. Only the case of a degenerate multiplet is shown here because it is only in this case that all of the parameters S through X are independent of the renormalization scale, μ . (This is in contrast with all of the previous examples we consider, which are μ -independent for any choices for the masses.) For a nondegenerate mirror fermion multiplet the parameter T develops a μ -dependence which is proportional to the square of the mass splittings within the multiplet.

There is a simple reason for the appearance of the μ dependence for a nondegenerate multiplet. The main point is that although a mirror doublet can acquire a common degenerate mass in an $SU_L(2) \times U_Y(1)$ -invariant way, renormalizable interactions can split the masses within a multiplet only if new, non-doublet, scalars are introduced and acquire a *vev*. As a result these scalars contribute to the parameter T at the tree level, and so this parameter must be renormalized — thereby developing a dependence on μ — just as must any other classical parameter.

- 5: The magnitude of S' and T' grows with the hypercharge and size of the colour representation for the multiplet concerned. Notice, however, that the overall contribution of a given fermion representation is significantly larger than that of additional scalars which transform in the same representation.

3. Conclusions

We have explored in this note the kinds of new physics which can produce deviations from the SM predictions for Z -pole physics in the direction of negative values for the Peskin-Takeuchi-like parameters S' and T' . We have been motivated to do so by the suggestive — if presently statistically inconclusive — reinforcement of the trend in this

direction found by fits to these oblique parameters which combine the most recent A_{LR} measurement with those at LEP.

We have found it to be reasonably easy to construct models for which the contributions of new physics to precision electroweak measurements are well approximated by purely oblique vacuum-polarization effects. It is more difficult, but not impossible, to obtain a correction which predicts S' and T' as large as -0.1 to -0.6 . New fermions are preferable to new scalars in this regard, since they generate vacuum polarizations which are systematically larger than the scalars, given similar couplings and masses.

In all cases we find that requiring relatively large contributions to the oblique parameters points to new particles whose masses are *not* very large compared to M_W or M_Z . We emphasize the necessity for interpreting the data on the Z pole (and the W mass) in this case in terms of the variables S', T' and U' , which are linear combinations of the usual variables, S, T, U with the new ones, V and X , of Ref. [9]. In fact, we find that the difference between the primed and unprimed parameters is important for allowing a larger region of parameter space to contribute acceptably to the electroweak parameters in these models.

This preference for comparatively light particles should have happy consequences should the central values continue to prefer negative S' and T' as the accuracy of the data improves. Since the new particles which we consider are comparatively light, they stand a good chance of being seen in other experiments once higher energies become directly observable. In particular, since it is the coupling of these particles to the W and the Z which is responsible for their contributions to the oblique vacuum polarizations, they should be directly pair-produced at LEP-200 if they are light enough for this to be kinematically allowed. Their effects can also be searched for in electroweak measurements at lower energies, $q^2 \simeq 0$, since their contributions to the oblique parameter X of Ref. [9] causes the value of $\sin \theta_w$ as measured at low energies to differ from that measured at $q^2 = M_Z^2$. Similarly, contributions to the parameter W give rise to deviations of the W width from its value as predicted by the SM supplemented by S, T and U . Signals at HERA or the TeVatron could also be expected (or not) depending on the more detailed

features of the new particles' masses and couplings.

Interestingly our analysis tends to disfavor an additional SM family of fermions, provided that it mixes with the usual three families, and that the lepton masses (especially the neutrino mass) are not too close to their present LEP lower limits $\simeq M_Z/2$. This reasoning goes along the same lines as those used to disfavor technicolor models [19].

However, it is clearly premature to be discarding models based on the size of their negative contributions to S' and T' . Our intention here is not to do this, we merely wish to determine what kinds of new-physics candidates can produce oblique corrections that are qualitatively in the right direction, should the trend to negative values for S' and T' ultimately become statistically significant. If this happens, we hope that our results for the magnitude of these parameters (and U') as functions of the assumed type of new physics will make a useful starting point for more detailed investigations.

Acknowledgments

We would like to thank Ken Ragan for helpful conversations, and Tom Rizzo for giving us access to the unpublished results of various recent fits to the data. This research was partially funded by funds from the N.S.E.R.C. of Canada, les Fonds F.C.A.R. du Québec, and the Swiss National Foundation.

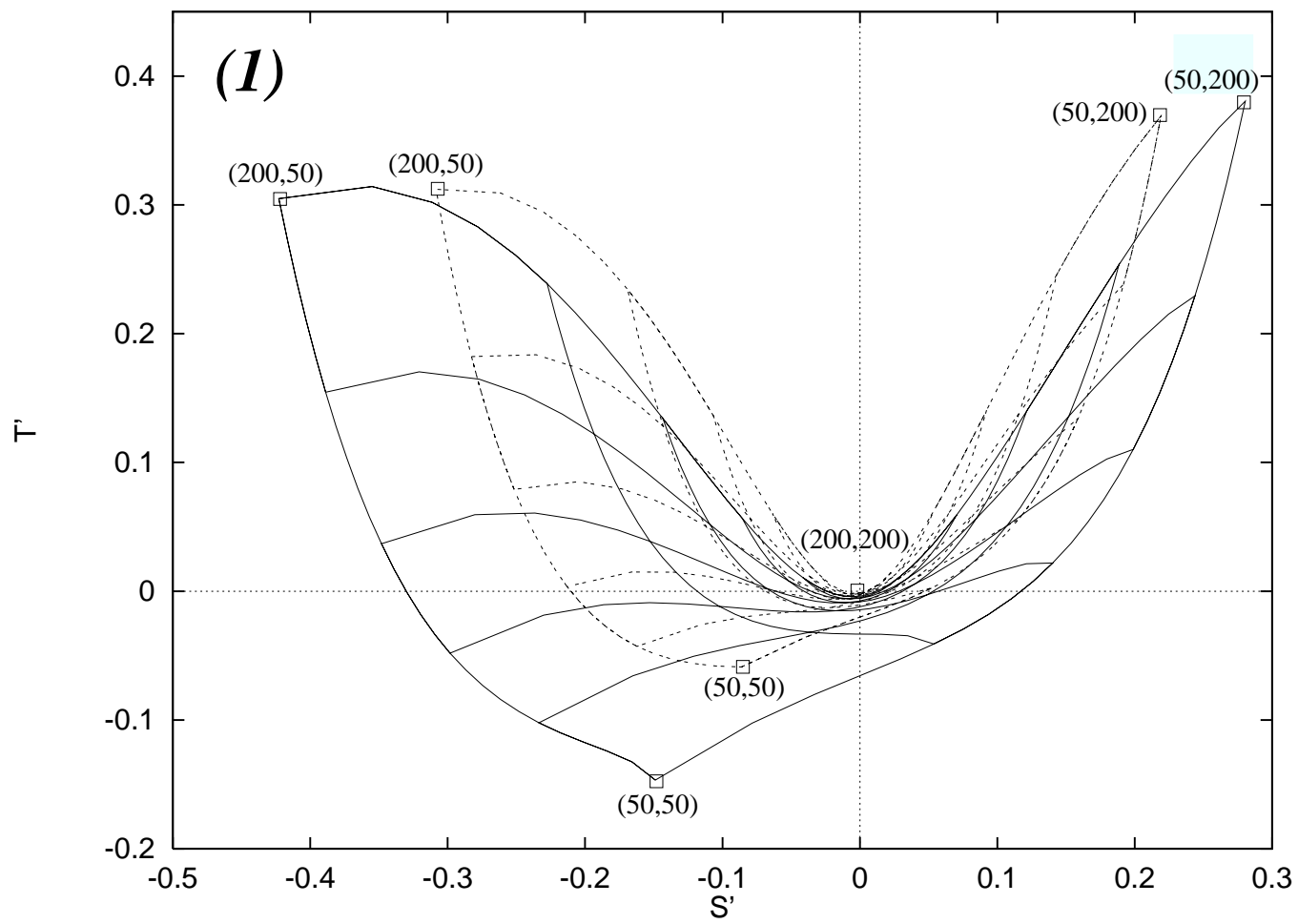
4. References

- [1] B. Pietrzyk, in the proceedings of the XXIXth Rencontres de Moriond, March 1994, preprint LAPP-EXP-94.07 (hep-ex/9406001).
- [2] The SLD Collaboration, F. Abe *et.al.*, preprint SLAC-PUB-6456, to appear in *Physical Review Letters*; M. Woods, *ibid*, preprint SLAC-PUB-6493.
- [3] J. Erler, preprint UPR-0619T (hep-ph/9406429).
- [4] B. Lynn, M. Peskin, R. Stuart, in *Physics at LEP* vol. 1, CERN Report 86-02, pp. 90 – 152.
- [5] M.E. Peskin and T. Takeuchi, *Phys. Rev. Lett.* **65** (1990) 964; *Phys. Rev.* **D46** (1992) 381.
- [6] M. Peskin, as quoted in Ref. [8] below.
- [7] H. Georgi, *Nucl. Phys.* **B363** (1991) 301; E. Gates and J. Terning, *Phys. Rev. Lett.* **67** (1991) 1840; E. Ma and P. Roy, *Phys. Rev. Lett.* **68** (1992) 2879; M. Luty and R. Sundrum, *Phys. Rev. Lett.* **70** (1993) 529; L. Lavoura, L.-F. Li, *Phys. Rev.* **D48** (1993) 234.
- [8] T.G. Rizzo, preprint SLAC-PUB-6455, to appear in *Phys. Rev. D*.
- [9] I. Maksymyk, C.P. Burgess and D. London, *Phys. Rev.* **D** (1994) (in press); C.P. Burgess, S. Godfrey, H. König, D. London and I. Maksymyk, *Phys. Lett.* **326B** (1994) 276.
- [10] G. Altarelli and R. Barbieri, *Phys. Lett.* **253B** (1991) 161; G. Altarelli, R. Barbieri and S. Jadach, *Nucl. Phys.* **B369** (1992) 3, (erratum) *ibid.***B376** (1992) 444; G. Altarelli, R. Barbieri and F. Caravaglios, *Nucl. Phys.* **B405** (1993) 3.
- [11] L. Lavoura and L.F. Li, *Phys. Rev.* **D49** (1994) 1409.

- [12] N. Evans, *Phys. Rev.* **D49** (1994) 4785.
- [13] Review of Particle Properties ,*Phys. Rev.* **D45** (1992) .
- [14] A. Zee, *Phys. Lett.* **161B** (1985) 141.
- [15] The CDF Collaboration, F. Abe *et al.*, *Phys. Rev. Lett.* **69** (1992) 3439.
- [16] The CDF Collaboration, F. Abe *et.al.*, *Phys. Rev.* **D48** (1993) 3939.
- [17] The H1 Collaboration, I. Abt *et.al.*, *Nucl. Phys.* **B396** (1993) 3; The ZEUS Collaboration, M. Derrick *et.al.*, *Phys. Lett.* **306B** (1993) 173.
- [18] F. Abe *et al.*, *Phys. Rev. Lett.* **64** (1990) 147, *Phys. Rev. Lett.* **68** (1992) 447. See also J.F. Gunion, D.W. McKay and H.Pois, preprint UCD-94-25 (hep-ph/9406249) and references therein.
- [19] M.E. Peskin and T. Takeuchi, *ibid.*; W.J. Marciano and J.L. Rosner, *Phys. Rev. Lett.* **65** (1990) 2963; D.C. Kennedy and P. Langacker, *Phys. Rev. Lett.* **65** (1990) 2967.

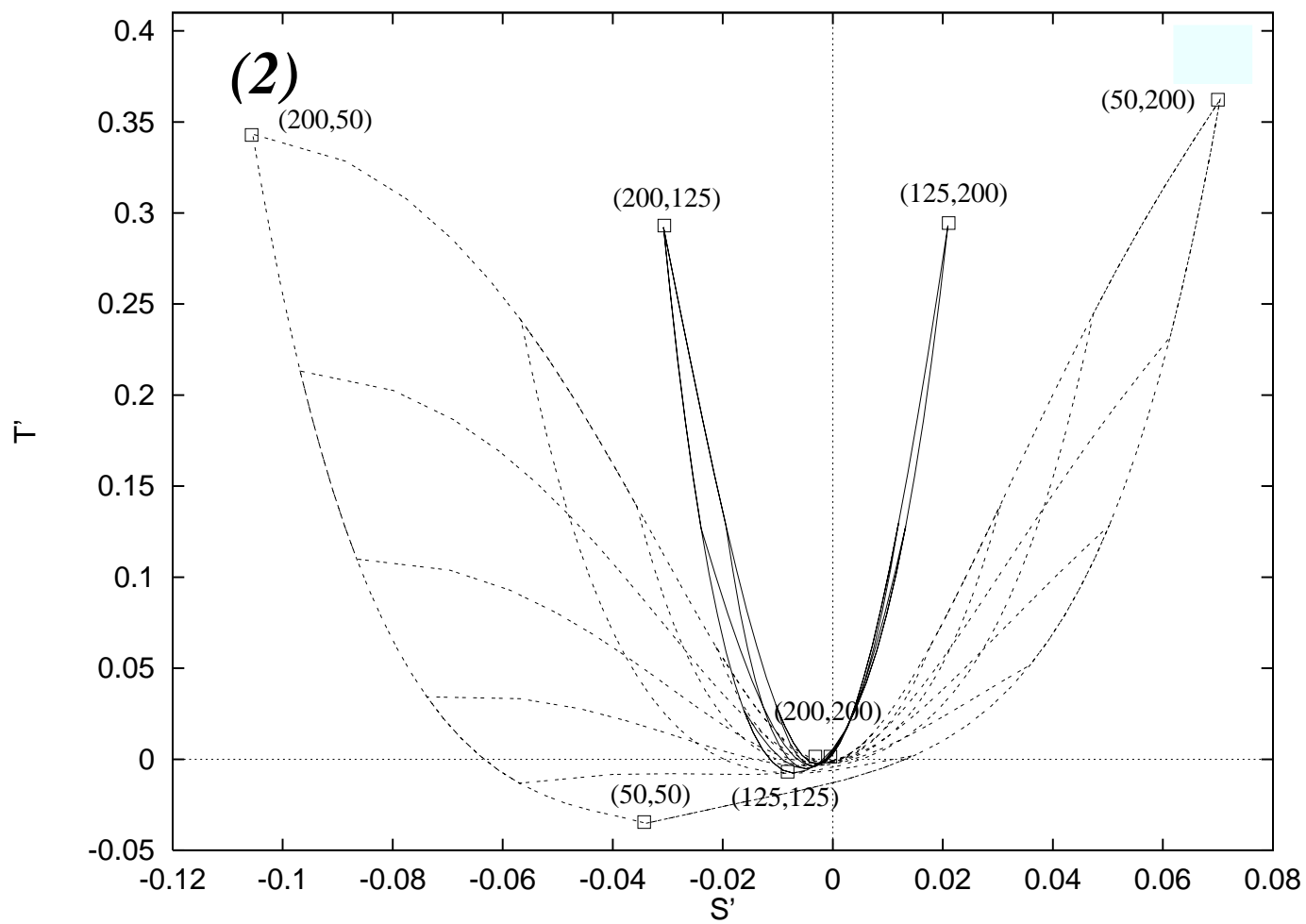
5. Figure Captions

- (1) The contribution of various scalar multiplets to the oblique electroweak parameters S' and T' . Solid line: a colour-singlet, $Y = 1$ triplet with masses $(m_2^2, m_1^2, m_0^2) = (a^2, \frac{1}{2}(a^2 + b^2), b^2)$, where a and b take the values given in brackets: (a, b) . Dotted line: A colour-singlet, $Y = \frac{3}{2}$ doublet with masses (m_2, m_1) as indicated in brackets. The grid in both cases represents steps of 30 GeV.
- (2) More scalar-generated oblique parameters. Solid line: a colour-triplet, $Y = \frac{1}{6}$ doublet (squarks) with masses $(m_{\tilde{u}}, m_{\tilde{d}})$. Dotted line: a colour-singlet, $Y = \frac{1}{2}$ doublet (a new Higgs or slepton *etc.*) with masses (m_1, m_0) . The grid indicates steps of 25 (resp. 30) GeV for the solid (resp. dotted) plots.
- (3) The oblique corrections due to a colour-singlet $Y = 0$ real triplet with masses (m_0, m_1) given in brackets. The grid spacing is 30 GeV.
- (4) More oblique parameters from scalar loops. Dotted line: a colour-singlet $Y = 0$ doublet with masses $(m_{\frac{1}{2}}, m_{-\frac{1}{2}})$. Solid line: a colour-singlet, $Y = 0$ real doublet plotted against its mass, $m_{\frac{1}{2}}$. The grid spacing is 30 (resp. 10) GeV for dotted (resp. solid) plots. Small Figure: Here the lower line reproduces the colour-singlet, $Y = 0$ real doublet as above, while the upper line gives a colour-singlet, $Y = 1$ singlet having mass (m_1) . The Grid spacing in both cases is 10 GeV.
- (5) The contribution of an extra SM family to the oblique parameters. Solid line: a colour-triplet, $Y = \frac{1}{6}$ quark doublet with masses $(m_{b'}, m_{t'})$ as indicated in brackets. Dotted line: a colour-singlet, $Y = \frac{1}{2}$ lepton doublet with masses $(m_{\nu'}, m_{l'})$. The grid spacing represents steps of 25 (resp. 30) GeV for the solid (resp. dotted) plots.
- (6) Oblique parameters due to colour-singlet mirror fermions. Solid line: a $Y = 1$ mirror singlet with mass (m_1) . Dotted line: a $Y = 0$ mirror doublet with (degenerate) mass $(m_{\frac{1}{2}})$. Dash-dotted line: a, $Y = \frac{1}{2}$ mirror doublet with (degenerate) mass $m_1 = m_0$. The grid spacing represents steps of 10 GeV for all three plots.



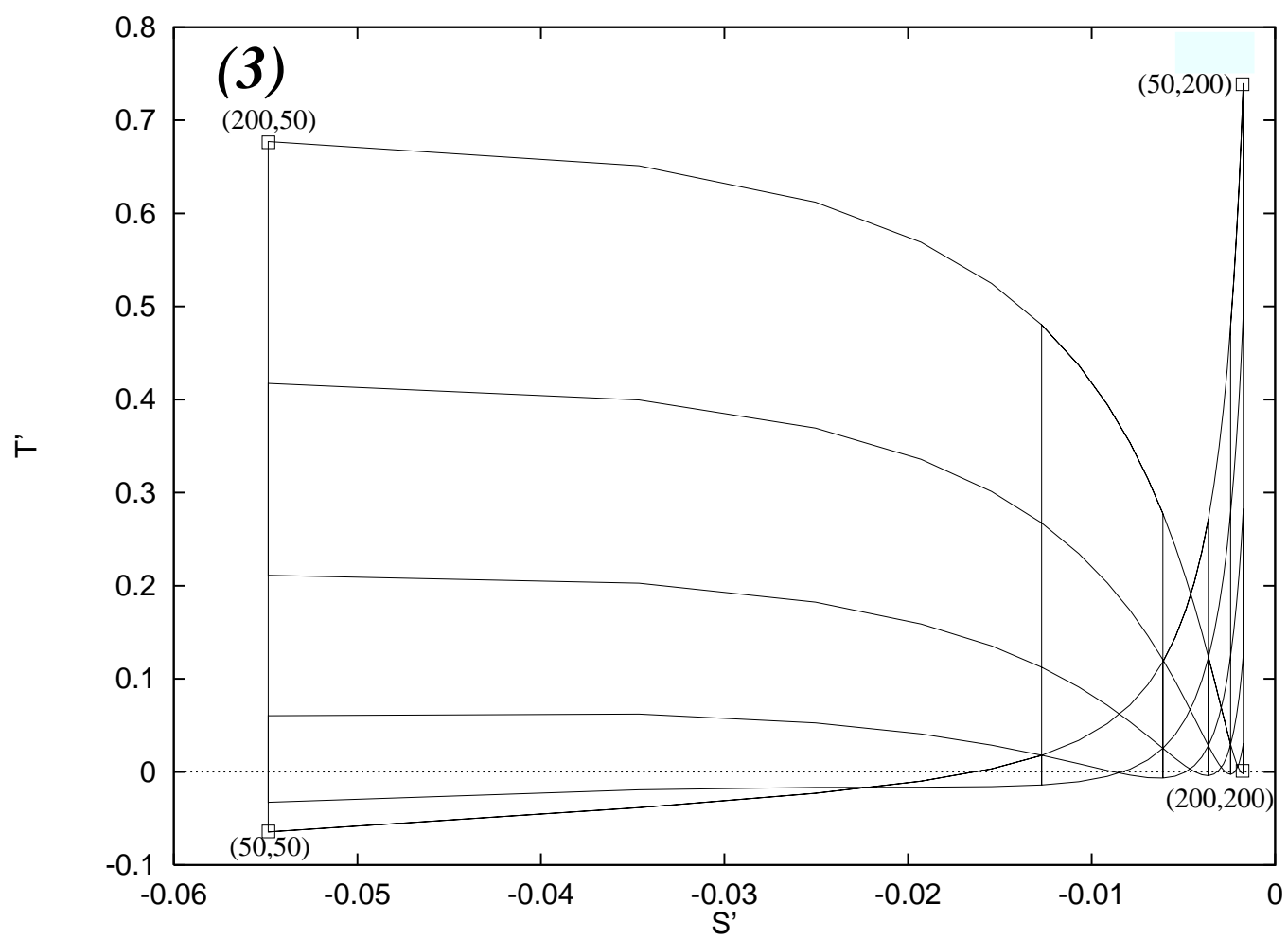
This figure "fig1-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9407203v1>



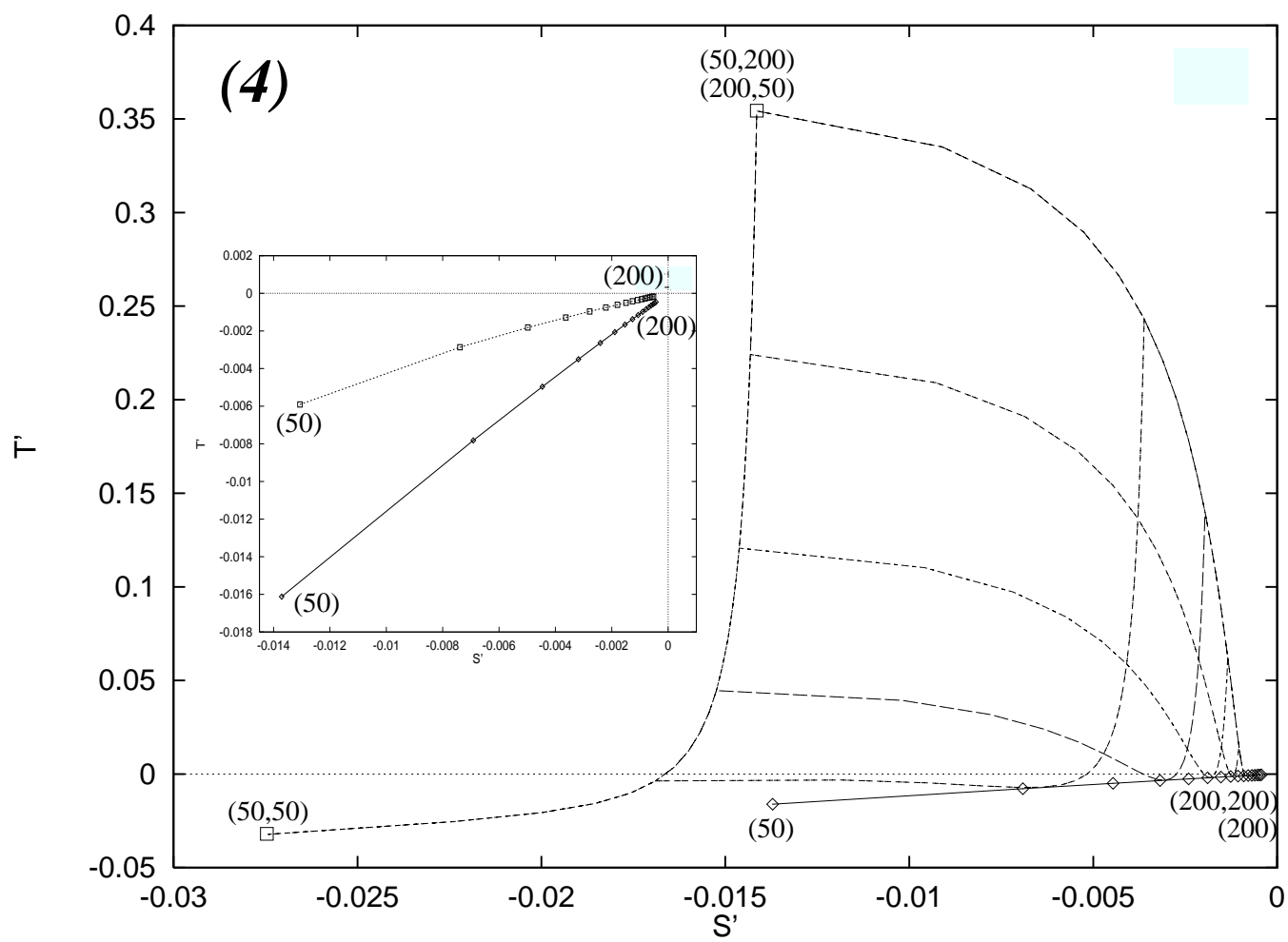
This figure "fig1-2.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9407203v1>



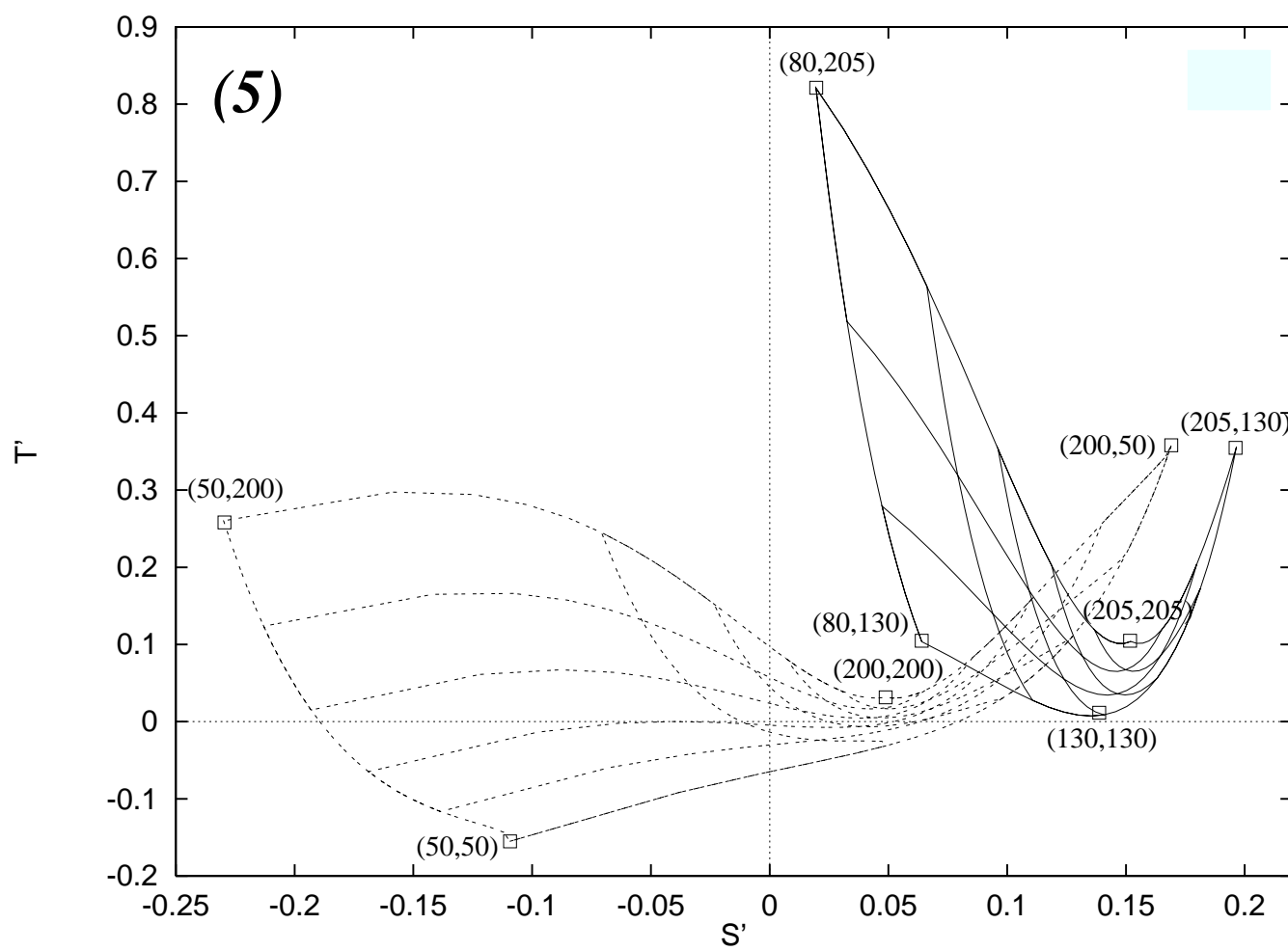
This figure "fig1-3.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9407203v1>



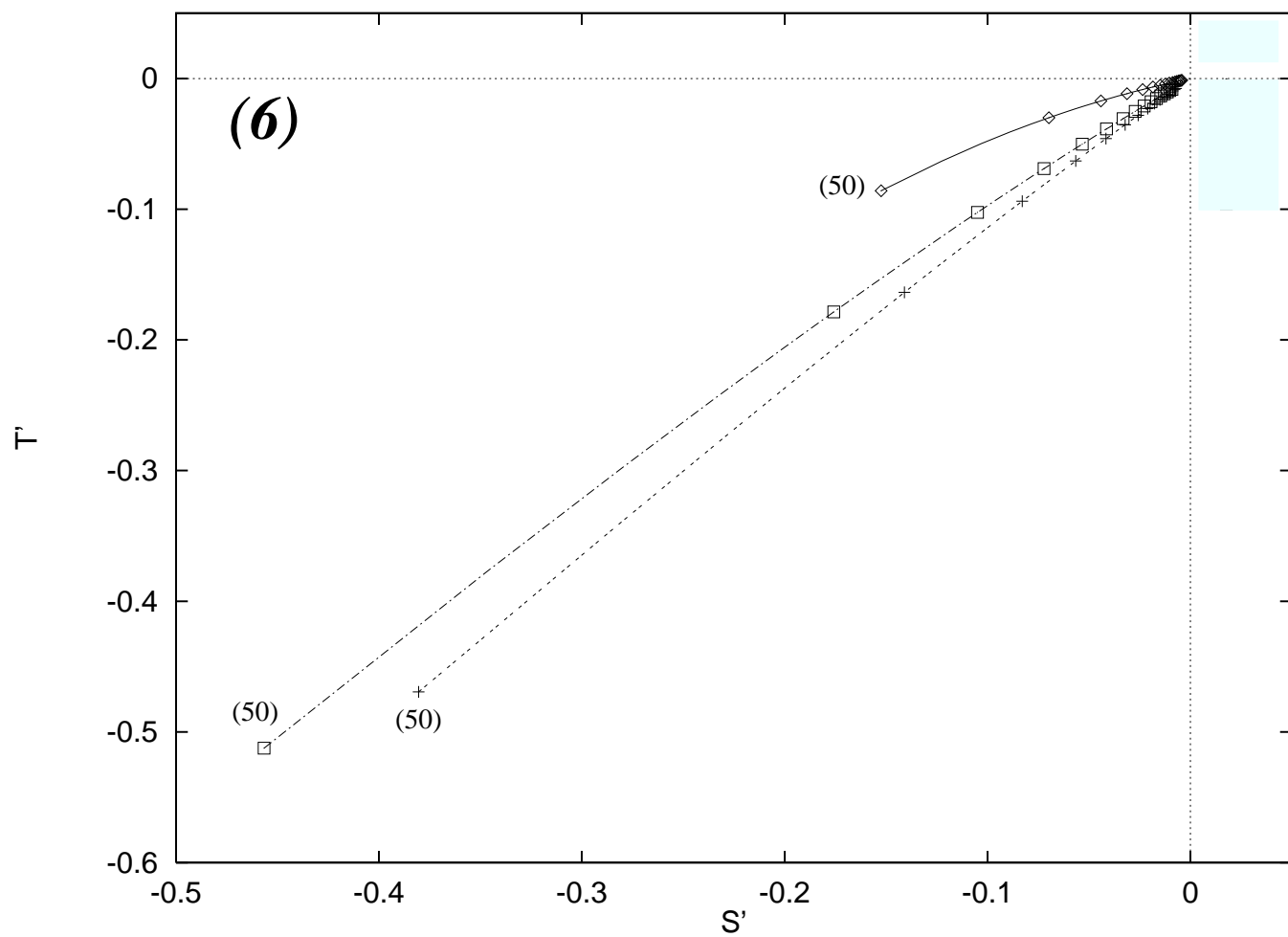
This figure "fig1-4.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9407203v1>



This figure "fig1-5.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9407203v1>



This figure "fig1-6.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9407203v1>